

Prospects for measuring the neutrino mass hierarchy with KM3NeT/ORCA

J. Hofestädt on behalf of the KM3NeT Collaboration

*Erlangen Centre for Astroparticle Physics, Friedrich-Alexander University of Erlangen-Nürnberg,
Erwin-Rommel-Str. 1, 91058 Erlangen, Germany*

ORCA (Oscillation Research with Cosmics in the Abyss) is the low-energy branch of KM3NeT, the next-generation research infrastructure hosting underwater Cherenkov detectors in the Mediterranean Sea. ORCA's primary goal is the determination of the neutrino mass hierarchy by measuring the matter-induced modifications on the oscillation probabilities of few-GeV atmospheric neutrinos. The ORCA detector design foresees a dense configuration of KM3NeT neutrino detection technology, optimised for measuring the interactions of neutrinos in the energy range of 3–20 GeV. To be deployed at the French KM3NeT site, ORCA's multi-PMT optical modules will exploit the excellent optical properties of deep-sea water to accurately reconstruct both shower-like (mostly electron neutrino) and track-like (mostly muon neutrino) events in order to collect a high-statistics sample of few-GeV neutrino events.

This contribution reviews the methods and technology of the ORCA detector, and discusses the prospects for measuring the neutrino mass hierarchy as well as the potential to improve the measurement precision on other oscillation parameters.

I. INTRODUCTION

A variety of experiments with solar, atmospheric, reactor and accelerator neutrinos, spanning energies from MeV up to tens of GeV, demonstrated unambiguously that neutrinos change from one flavour to another during propagation. Neutrino oscillations imply non-zero neutrino masses, and that the masses of the three neutrino states are different. In the standard 3-neutrino scheme, the mixing matrix relating the neutrino flavour eigenstates (ν_e , ν_μ , ν_τ) to the mass eigenstates (ν_1 , ν_2 , ν_3) is parameterised in terms of three mixing angles θ_{12} , θ_{13} and θ_{23} , and a CP-violating phase δ_{CP} . Oscillation experiments are mostly sensitive to mass-squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$ ($i, j = 1, 2, 3$). Global fits of available data form a coherent picture and provide the values of these oscillation parameters with reasonable precision [1].

An open question is the so-called neutrino mass hierarchy (NMH). It refers to the ordering of the neutrino mass eigenstates, which is either $\nu_1 < \nu_2 < \nu_3$ (normal hierarchy, NH) or $\nu_3 < \nu_1 < \nu_2$ (inverted hierarchy, IH). The ordering of the first two closely spaced mass eigenstates, $\nu_1 < \nu_2$, is known from solar neutrino physics. Further yet unknown neutrino properties are: the value of δ_{CP} , the absolute masses, the Dirac/Majorana nature of neutrinos. Knowing the NMH is important for constraining the models that seek to explain the origin of mass in the leptonic sector and will allow to optimise the information obtained from other neutrino experiments (targeting δ_{CP} , absolute neutrino masses and neutrinoless double-beta decays). In addition, the NMH has a significant impact on the measurement precision of the oscillation parameters.

The NMH can be determined by measuring the energy and zenith angle dependent oscillation pattern of

few-GeV atmospheric neutrinos that have traversed the Earth towards the detector [2]. Due to matter-induced modifications on the oscillation probabilities in conjunction with different cross-sections and atmospheric neutrino fluxes for neutrinos and antineutrinos, the expected event rates of neutrinos in the energy regime of 3–20 GeV are different for NH and IH.

Next-generation experiments, such as KM3NeT/ORCA [3], PINGU [4] and Hyper-Kamiokande [5], are planned to perform this measurement with megaton-scale water/ice-based Cherenkov detectors.

In the following, the prospects for measuring the neutrino mass hierarchy with ORCA (Oscillation Research with Cosmics in the Abyss) are presented, and the potential to improve the measurement precision on θ_{23} and Δm_{32}^2 is discussed.

This contribution is mainly based on the ‘Letter of Intent for KM3NeT 2.0’ [3].

II. THE KM3NET/ORCA DETECTOR

The KM3NeT detector design builds on the experience of the successful deployment and operation of the ANTARES detector [6], which has demonstrated the feasibility of measuring neutrinos with a large-volume Cherenkov detector in the deep sea. The detection principle is that of a 3-dimensional array of photo-sensors that register the Cherenkov light induced by charged particles produced in a neutrino-induced interaction. From the arrival time of the Cherenkov photons (nanosecond precision) and the position of the sensors (~ 10 cm precision), the energy and direction of the incoming neutrino, as well as other parameters of the neutrino interaction, can be reconstructed.

A key KM3NeT technology is the Digital Optical Module (DOM), a pressure-resistant glass sphere

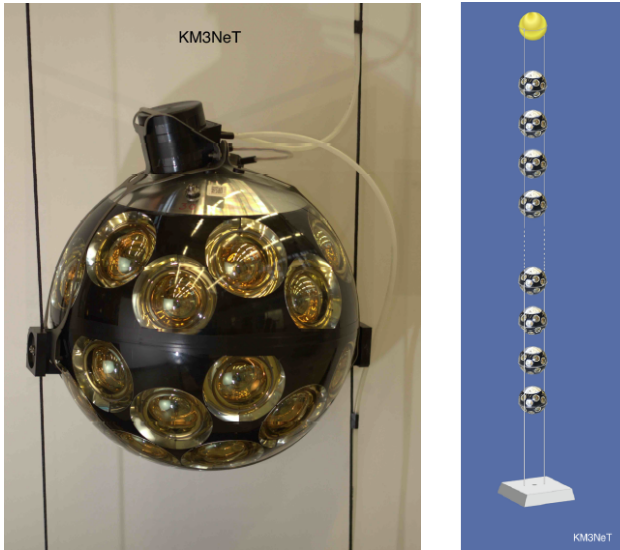


FIG. 1: Photograph of a DOM (left) and schematic drawing of an detection string (right).

housing 31 3-inch PMTs and their associated electronics. This multi-PMT design offers several improvements compared to traditional optical modules hosting only a single large PMT (for example in ANTARES), most notably: larger photocathode area, wider field of view, directional information and dynamic range. The DOMs are arranged in strings held vertically by a buoy and anchored to the seabed. Figure 1 shows a DOM and a detection string.

In its current design, the ORCA detector will comprise 115 such detection strings. Each string comprises 18 DOMs with a vertical spacing of about 9 m. The horizontal spacing between adjacent strings is roughly 20 m. The instrumented mass is about 6 Mton of seawater. This detector configuration is the outcome of an optimisation study using the NMH sensitivity as figure of merit. The proposed detector could be built in three years, with an investment budget of about 45 M€ [7].

The ORCA detector will be deployed at the French KM3NeT site at a depth of 2450 m. The site is about 40 km offshore from Toulon and about 10 km west of the operating ANTARES detector.

The construction of the infrastructure has already started. The first main electro-optical cable and the first junction box, needed to connect the detection strings, have been successfully deployed and connected. The first detection string is foreseen to be deployed in early 2017. An array comprising 7 detection strings is funded and expected to be concluded and operational by the end of 2017. It will serve to demonstrate the feasibility of the measurement and to validate and optimise the detector design. The full-size ORCA detector comprising 115 detection strings could be operational towards 2020.

Within KM3NeT, the same technology is employed also for the search for high-energy astrophysical neutrino sources with the ARCA detector [8], which will be deployed offshore from Sicily, Italy. The main difference between both detector designs is the density of photosensors, which is optimised for the study of neutrinos in the few-GeV (ORCA) and TeV-PeV (ARCA) energy ranges.

III. EXPECTED DETECTOR PERFORMANCE

The key parameters for the NMH determination are the effective mass of the detector and the experimental resolutions for the energy E_ν and zenith angle θ_ν of the incoming neutrino.

Detailed Monte Carlo simulations have been performed using GENIE [9] for simulating neutrino interactions and GEANT-based simulation packages [10, 11] for particle propagation and Cherenkov photon generation. Optical background from ^{40}K decays in the seawater as well as the background from down-going atmospheric muons is taken into account. Further details are given in [3].

Two distinct event topologies are considered: tracks and showers. Showers are initiated by energetic electrons and hadrons emerging from the neutrino interaction, and develop over relatively short distances. Muons produce elongated tracks in the detector. Therefore, track-like events are induced by $\bar{\nu}_\mu$ charged-current (CC) interactions, as well as $\bar{\nu}_\tau$ CC interactions with muonic tau decays. All other neutrino-induced events are called shower-like, i.e. $\bar{\nu}_e$ CC events, $\bar{\nu}_{e,\mu,\tau}$ neutral-current events and $\bar{\nu}_\tau$ CC events with non-muonic τ decays.

Dedicated reconstruction strategies for track-like and shower-like events, as well as an event topology classification algorithm, have been developed and are described in [3]. The energy resolution is Gaussian-like with $\sigma_{E_\nu}/E_\nu \approx 25\%$. The median zenith angle resolution is about 5° for $\bar{\nu}_e$ CC and $\bar{\nu}_\mu$ CC events with $E_\nu = 10$ GeV. Due to the long scattering length of light in deep-sea water, the reconstructions are able to find the lepton (e, μ) in $\bar{\nu}_{e,\mu}$ CC events and are therefore able to gain access to the interaction inelasticity y . This allows a statistical separation of ν and $\bar{\nu}$ interactions to further add to the NMH sensitivity [12]. This possibility has not yet been exploited in the estimated NMH sensitivity presented below. As shown in [13], the energy resolution is dominated by intrinsic light yield fluctuations in the hadronic shower and the direction resolution is limited by the kinematic scattering angle between the outgoing lepton and the incoming neutrino.

The purity of the event topology classification is about 90% (70%) for $\bar{\nu}_e$ CC ($\bar{\nu}_\mu$ CC) events with $E_\nu = 10$ GeV. The same event classification algorithm

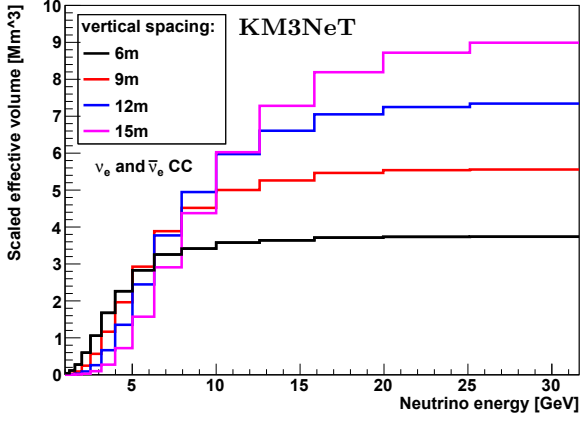


FIG. 2: Effective volume as a function of neutrino energy E_ν for $\bar{\nu}_e$ CC events. Detector configurations with different vertical spacings between the DOMs are shown as different colours.

also rejects downgoing atmospheric muons that are mis-reconstructed as upgoing. A contamination of less than a few percent of atmospheric muons in the final sample of upgoing neutrino events is achieved.

The effective mass of the detector is about 6 Mton, being reached for $\bar{\nu}_e$ CC and $\bar{\nu}_\mu$ CC with energies above $E_\nu = 10$ GeV, while 50% efficient at 4 GeV. Figure 2 shows the effective volume for $\bar{\nu}_e$ CC events for detector configurations with different vertical spacings between the DOMs, i.e. different photosensor densities. In the $E_\nu = 5 - 10$ GeV range, which is most relevant for the NMH determination, the detector configuration with 9 m vertical spacing provides the largest effective mass and therefore largest available event statistics. This detector configuration was also found to provide the best NMH sensitivity [3]. It will provide data samples of about 50,000 reconstructed upgoing neutrinos per year.

IV. SENSITIVITY TO NEUTRINO MASS HIERARCHY AND MORE

Building on the expected detector performance, a significance analysis is performed by generating a large number of pseudo-experiments (PEs) with event distributions in the reconstructed E_ν - θ_ν plane. For each PE, a true hierarchy and a set of oscillation parameters is assumed. Each PE is analysed by performing a maximum likelihood fit with the oscillation parameters as free parameters and assuming either NH or IH. The likelihood ratio resulting from these fits is used to quantify the separability between both hierarchies.

Systematic uncertainties from the neutrinos fluxes, their cross sections as well as the detector response are parameterised as overall normalisation, energy scale,

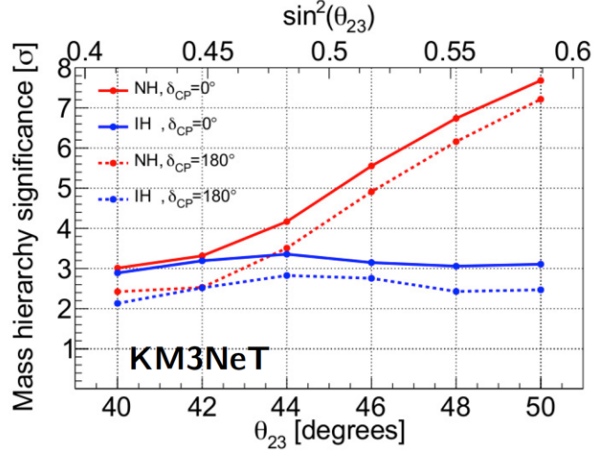


FIG. 3: Median NMH significance to exclude the other hierarchy hypothesis assuming true NH (red) or IH (blue) as a function of true θ_{23} and assuming $\delta_{CP} = 0$ (solid) or $\delta_{CP} = \pi$ (dashed). Three years of data taking with the full-size ORCA detector are assumed.

$\bar{\nu}/\nu$ skew, μ/e skew and NC/CC skew and are incorporated as nuisance parameters. It is found that none of these effects compromise substantially the ability of ORCA to determine the NMH [3].

Figure 3 shows the median significance of ORCA to exclude the wrong hierarchy hypothesis after three years of data taking as a function of the true value of θ_{23} and assuming no CP-violation, i.e. δ_{CP} equals 0 or π . For the experimentally allowed range of θ_{23} and assuming $\delta_{CP} = 0$, the NMH can be measured with about 3σ after three years of operation. ORCA is moderately sensitive to the CP-phase, the significance being reduced by at most 0.5σ if $\delta_{CP} = \pi$ is realised in nature. The significance increases dramatically in case of NH and $\theta_{23} > \pi/4$, reaching up to about 7σ in three years of operation.

Besides the NMH determination, ORCA can also improve the uncertainties on Δm_{32}^2 and θ_{23} . Both parameters are determined without the need for constraints from global data in conjunction with the NMH. Figure 4 shows the expected measurement precision after three years and compares it with current results of other experiments and their predicted performances in 2020. The precision of ORCA is comparable or better, and is obtained with different systematic uncertainties. In particular, ORCA can determine the octant of θ_{23} (above or below 45°) for a wide range of the allowed parameter range.

Additional science topics of ORCA include: testing the unitarity of the neutrino mixing matrix by studying $\bar{\nu}_\tau$ appearance; indirect searches for sterile neutrinos, non-standard interactions and other exotic physics; indirect searches for dark matter; testing the chemical composition of the Earth's core (Earth tomography); and low-energy neutrino astrophysics. Pre-

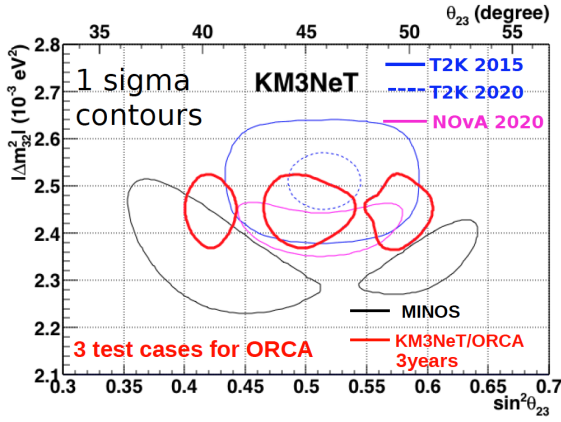


FIG. 4: One sigma contours of the measurement precision in Δm_{32}^2 and θ_{23} after three years of data taking with ORCA for three assumed test cases (red). The current results from MINOS (back) and T2K (blue solid) are indicated, as well as the predicted performance of NOνA (magenta) and T2K (blue dashed) in 2020. All contours are at 1σ for NH.

liminary performance expectations are briefly summarised in [7]. The KM3NeT research infrastructure will also house instrumentation for Earth and Sea sciences, such as marine biology, oceanography and geophysics.

Possible future options could be a long-baseline neutrino beam targeted to ORCA [14], and a significantly

denser detector instrumentation lowering the detection threshold to measure the CP-phase δ_{CP} with atmospheric neutrinos [15].

V. CONCLUSIONS

With ORCA, a 6 Mton deep-sea Cherenkov detector optimised for the detection of few-GeV neutrinos, the KM3NeT Collaboration aims to perform a high-statistics measurement of the zenith angle and energy dependent event rates of atmospheric neutrinos that have traversed the Earth. The oscillated neutrino flux in the energy range 3–20 GeV holds the key to determine the neutrino mass hierarchy. ORCA is expected to achieve a $3\text{--}7\sigma$ sensitivity to the neutrino mass hierarchy in three years of data taking. Simultaneously, ORCA will measure Δm_{32}^2 and θ_{23} with competitive precision, and has a rich additional science program.

In the first construction phase of ORCA, a 7-string demonstrator is expected to be concluded and operational by the end of 2017. The full-size ORCA detector could be operational towards 2020, so that the neutrino mass hierarchy might be resolved as early as 2023.

Further details can be found in the recently published ‘Letter of Intent for KM3NeT 2.0’ [3].

-
- [1] I. Esteban, et al., *Updated fit to three neutrino mixing: exploring the accelerator-reactor complementarity* (2016), [arXiv:1611.01514 \[hep-ph\]](#).
 - [2] E. K. Akhmedov, S. Razzaque and A. Y. Smirnov, *Mass hierarchy, 2-3 mixing and CP-phase with huge atmospheric neutrino detectors*, JHEP **2** (2013) 82 [Erratum JHEP **7** (2013) 26], [\[arXiv:1205.7071 \[hep-ph\]\]](#).
 - [3] S. Adrián-Martínez et al., *Letter of Intent for KM3NeT 2.0*, J. Phys. G **43** (2016) 084001, [\[arXiv:1601.07459 \[astro-ph.IM\]\]](#).
 - [4] M. G. Aartsen et al., *PINGU: A Vision for Neutrino and Particle Physics at the South Pole* (2016), [arXiv:1607.02671 \[hep-ex\]](#).
 - [5] K. Abe et al., *A long baseline neutrino oscillation experiment using J-PARC neutrino beam and Hyper-Kamiokande* (2014), [arXiv:1412.4673 \[physics.ins-det\]](#).
 - [6] M. Ageron et al., *ANTARES: the first undersea neutrino telescope*, Nucl. Instrum. Meth. **A656** (2011) 11, [\[arXiv:1104.1607 \[astro-ph.IM\]\]](#).
 - [7] P. Coyle, *KM3NeT-ORCA: Oscillation Research with Cosmics in the Abyss* (2017), [arXiv:1701.01382 \[physics.ins-det\]](#).
 - [8] R. Coniglione, *High-energy neutrino astronomy with KM3NeT-ARCA*, (2017), [arXiv:1701.05849 \[astro-ph.IM\]](#).
 - [9] C. Andreopoulos et al., *The GENIE Neutrino Monte Carlo Generator*, Nucl. Inst. Meth. **A614** (2010) 87, [\[arXiv:0905.2517 \[hep-ph\]\]](#).
 - [10] A. G. Tsirigotis, A. Leisos and S. E. Tzamarias, *HOU reconstruction & simulation (HOURS): A complete simulation and reconstruction package for very large volume underwater neutrino telescopes*, Nucl. Inst. Meth. **A626-627** (2011) S185.
 - [11] A. Margiotta, *Common simulation tools for large volume neutrino detectors*, Nucl. Instrum. Meth. **A725** (2013) 98.
 - [12] M. Ribordy and A. Y. Smirnov, *Improving the neutrino mass hierarchy identification with inelasticity measurement in PINGU and ORCA*, Phys. Rev. D **87** (2013) 113007, [\[arXiv:1303.0758 \[hep-ph\]\]](#).
 - [13] S. Adrián-Martínez et al., *Intrinsic limits on resolutions in muon- and electron-neutrino charged-current events in the KM3NeT/ORCA detector* (2016), [arXiv:1612.05621 \[physics.ins-det\]](#).
 - [14] J. Brunner, *Counting Electrons to Probe the Neutrino Mass Hierarchy* (2013), [arXiv:1304.6230 \[hep-ex\]](#).
 - [15] S. Razzaque and A. Y. Smirnov, *Super-PINGU for measurement of the leptonic CP-phase with atmospheric neutrinos*, JHEP **5** (2015) 139, [\[arXiv:1406.1407 \[hep-ph\]\]](#).